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The use of natural stream characteristics for stream rehabilitation works below the Manitoba escarpment

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ABSTRACT

Drainage improvement of watersheds draining from the Manitoba escarpment have been based on channel designs which result in nearly straight canals with uniform gradients and trapezoidal cross sections. These conditions are often associated with environmental degradation, such as loss of fish spawning and rearing habitat, increased erosion and siltation, and changes in water conveyance patterns that can cause property damage. In mobile bed streams, the geometry of the "natural" stream channel in profile and in cross section is determined by the geology of the basin, the extent of the tributary drainage area, and the position of a stream reach in the hierarchical order of the drainage network. Regional stream channel characteristics can be determined from channel surveys in sample reaches that are selected throughout the basin. Selected aspects of the "natural" stream geometry can then be mimicked in rehabilitation schemes that enhance or create physical stream characteristics in the uniform drainage canals that are significant biologically and hydraulically. Experimental rehabilitation and enhancement works have been constructed in Wilson Creek and Mink River. The works have re-stabilized the channels and created new pool and riffle habitats for fish spawning and rearing.

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THE USE OF NATURAL STREAM CHARACTERISTICS FOR STREAM REHABILITATION WORKS BELOW THE MANITOBA ESCARPMENT

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INTRODUCTION

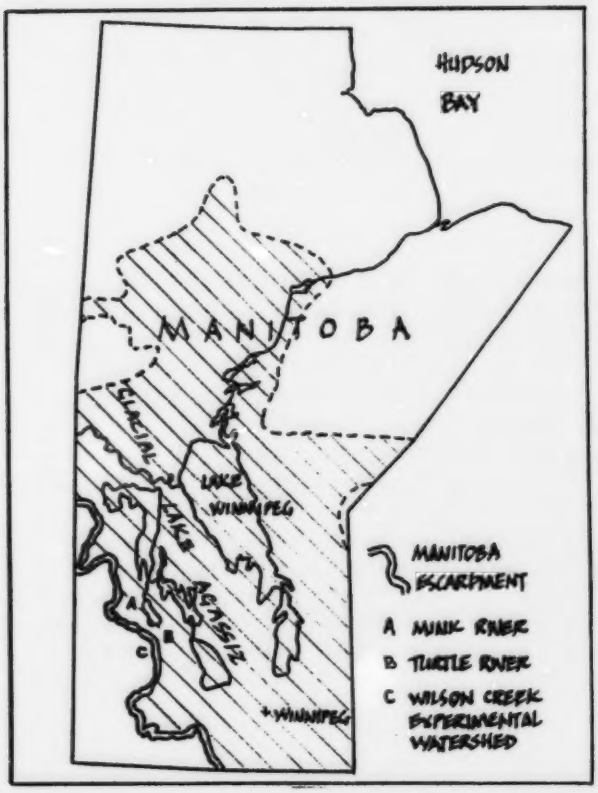

Figure 1: The Manitoba escarpment of Cretaceous shales and limestones and the glacial Lake Agassiz plain in central Manitoba showing the location of stream rehabilitation works in the Mink River, Turtle River and Wilson Creek drainage basins.

The channelization and extension of stream channels to drain wetlands on the western edge of the flat glacial Lake Agassiz plain in south-central Manitoba (Figure 1) has caused two major types of stream instability to occur: in the upper reaches, a series of dramatic canyons have been eroded through alluvial fan deposits that lie along the foot of the Manitoba escarpment; while in the lower reaches, meandering stream channels have been straightened and enlarged to increase their flood discharge capacity, causing downcutting and bank instability. For example, in the 2,064 square km Turtle River basin that lies on the Lake Agassiz plain adjacent to the Riding Mountain portion of the escarpment (Figure 2), over 600 square km were directly connected to the downstream drainage network by excavating channels across alluvial fans to headwater streams on the escarpment. Consequently, the downstream channels between

the foot of the escarpment and the main stem of the Turtle River were straightened and enlarged to conduct increased flood peaks and sediments from the steep headwater basins. Flood peaks were further increased by excavating local tributary channels that followed the square mile grid pattern of public road allowances in the agricultural zone (Figure 2).

Extension of the drainage network and channelization has significantly reduced fisheries and other biologically important habitats in the stream channels and downstream lakes. The diverse hydraulic conditions created by meandering channels and pools and riffles, and the habitats affected by overhanging banks and shading from near-stream vegetation are required, for example, for some species of fish for spawning, rearing, and feeding (Beschta and Platts 1986). Studies in the Lake Dauphin basin adjacent to the Duck Mountain and Riding Mountain segments of the escarpment have shown that segments of all of the tributary streams have been straightened and channelized (Chapman 1987a). Clearing and increased drainage efficiency has increased spring runoff flood peaks while reducing their duration, shortening the available periods for fish spawning and egg incubation in streams to below critical levels in normal and dry years (Gaboury 1985). Alluvial fan and downstream channel erosion has increased the turbidity and sedimentation rates in the Lake Dauphin basin, contributing to the collapse of the commercial fishery by 1970 (Penner and Oshoway 1982, Manitoba Water Commission 1984).

Similar physical and biological effects of channelization and drainage extension have been reported in many other studies (for example, Emerson 1971, Keller 1976, Parker and Andres 1976, and National Research Council 1982). In some cases, stream rehabilitation works have been undertaken to re-stabilize channels and to restore some of the natural habitat characteristics. For example, pool and riffle sequences have been re-created using low-head dams (Jackson 1974, Keller 1975); jetties, groins, and other bank protection measures have been used to re-stabilize eroding reaches (Tourbier and Westmacott 1981); meandering channel patterns and overbank vegetation have been restored (Glitz 1983, Bolliger et al. 1984); and methods for designing channel rehabilitation works based on natural stream relationships have been proposed (Nunnally 1985, Heede 1986).

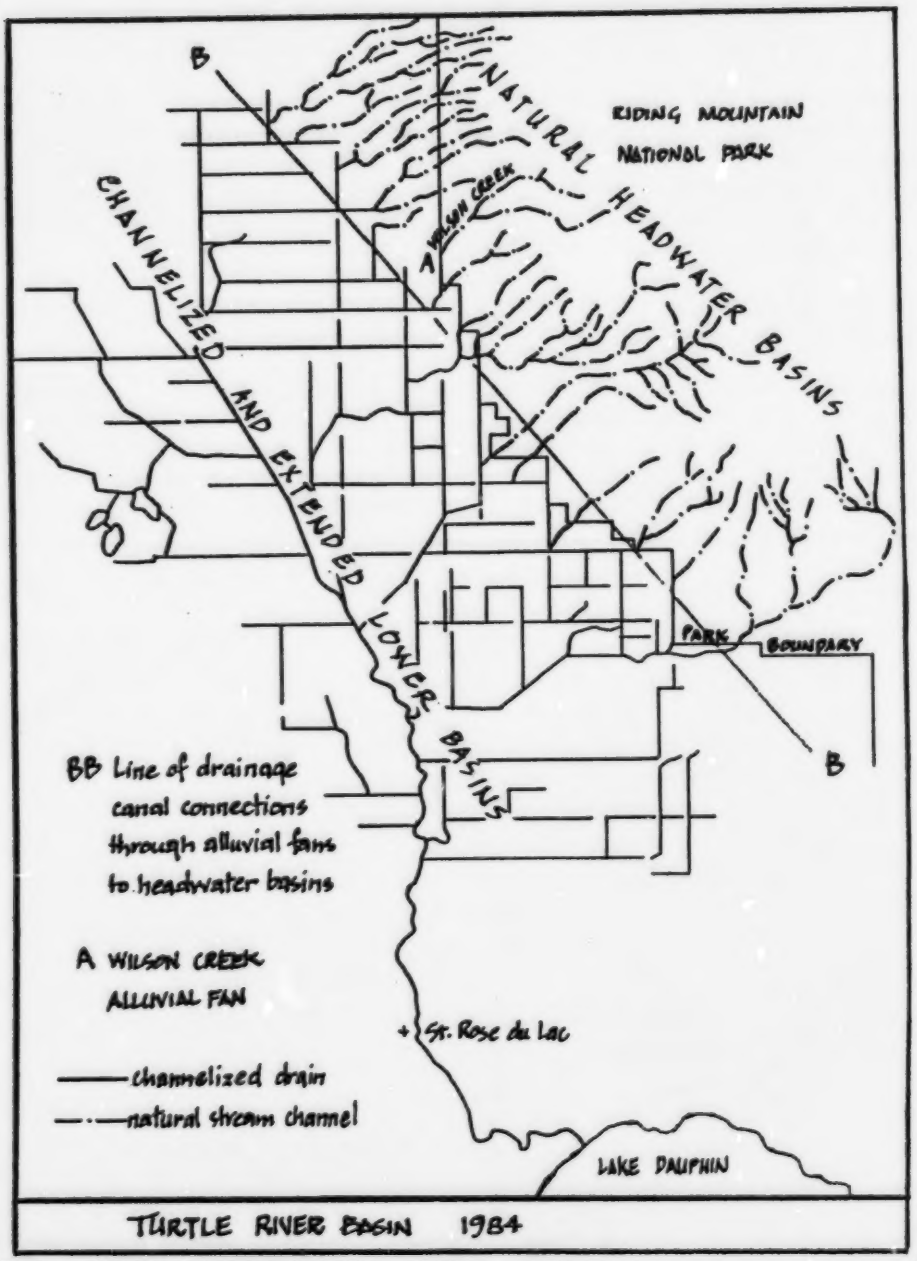

Figure 2: The Turtle River drainage basin. The headwater basins in Riding Mountain National Park, lying to the right of the line of alluvial fans at the foot of the escarpment (marked BB) have not been channelized. The remaining lower basin has been cleared and covered with a network of excavated drainage channels. The drains have been extended westwards to connect the mainstem of the Turtle River directly to the headwater basins through the alluvial fans, increasing flood peaks in the lower basin and re-transporting the fan deposits further downstream.

EXPERIMENTAL STREAM REHABILITATION WORKS BELOW THE MANITOBA ESCARPMENT

Experimental stream rehabilitation works based on natural pre-development characteristics have been constructed and tested in two streams flowing into Lake Dauphin: 1) on the Wilson Creek alluvial fan below the Riding Mountain segment of the escarpment and 2) on the channelized portion of the lower Mink River flowing from the Duck Mountain segment of the escarpment.

1) Gradient Control Dams To Prevent Further Headcutting Through The Wilson Creek Alluvial Fan

Between 1910 and 1927 as land clearing and homesteading took place on the Wilson Creek alluvial fan, several small drainage canals were extended westwards from the mainstem of the Turtle River to drain wetlands that were caused by seepage from the upper fan area (Figure 3). The groundwater reservoir in the fan

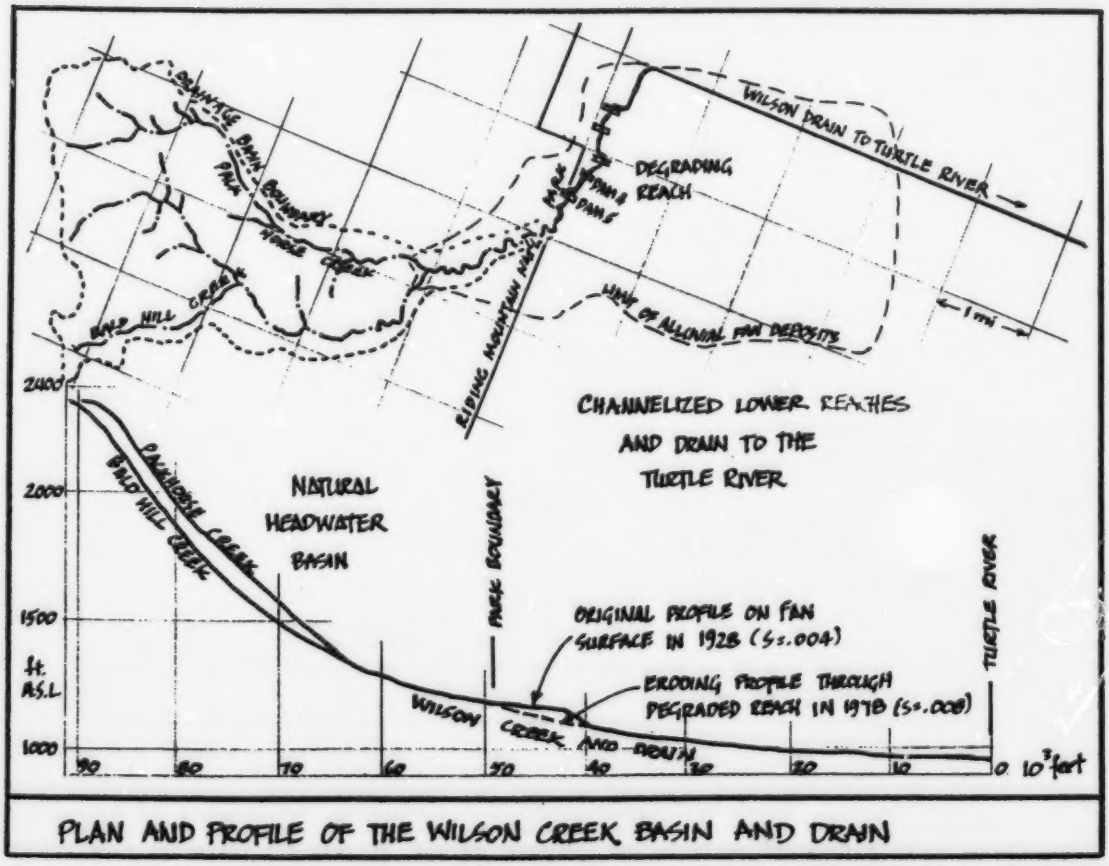

Figure 3: The Wilson Creek headwater basin and drainage channel connecting it to the Turtle River. The connecting channel has headcut and migrated 3 km through the alluvial fan in 50 years. Two experimental gradient control dams constructed in 1980 have stabilized the upper end of the degrading reach.

was continuously recharged by the infiltration of all of the Wilson Creek flows from the escarpment into the coarse shale deposits of the upper fan reach. In 1928, a single drainage canal was extended further westwards into the upper fan area to capture the Wilson Creek flows and conduct them directly to the Turtle River in the hope that seepage into the lower fan areas would decrease. The drainage canal was successfully connected to the mainstem of the creek at the foot of the escarpment but a rapid sequence of headcutting and degradation occurred as flood flows were conducted in the single steep channel across the fan rather than spreading and infiltrating into the fan surface. In effect, the hydraulic energy of the stream was concentrated in the single channel, allowing the flows to re-erode the former deposits and carry them further downstream into the lower gradient drainage network. To maintain the channel capacity in the Wilson drain to conduct the floodwaters to the Turtle River without flooding the adjacent farmlands, additional energy is required. In this case, it is supplied by diesel fuel burned in earth-moving machinery that regularly removes the re-deposited fan sediments from the drainage network.

From regular surveys undertaken as part of the Wilson Creek Experimental Watershed study (Wilson Creek Headwater Control Committee 1983) between 1957 and 1978 and from aerial photographs of the fan area, taken fortuitously in 1928 before the creek channel was connected to the lower drainage network, 15 cross-sections of the fan were re-created to determine the rate of headcutting and degradation (Newbury 1980). The total volume of former deposits eroded in the 50 year period was estimated to be 700,000 cubic m, or 14,000 cubic m per year. The average annual sediment load delivered to the fan from the escarpment is estimated to be 5,300 cubic m (Vitkin 1979). In effect, the drainage network below the fan area was subject to sediment deposition that is 4 times greater than the natural rate of delivery from the 22 square km basin of Wilson Creek, requiring that the canal be re-excavated every 2 - 3 years (Bowering 1987).

To stop head-cutting through the alluvial fan and to decrease the input of sediment to the Wilson Creek drain and ultimately Lake Dauphin, five sites for low (~1.8m) rock-fill dams were located along the 2.3 km fan reach to decrease the channel gradient to its pre-development value and reduce the hydraulic energy of flood flows through the fan reach. The slope of the pre-development depositional channel across the fan surface in 1928 was 0.4 percent. By 1978, the slope of the eroding channel through the fan had doubled to 0.8 percent. To restore the original gradient, 9.2 m of the total fall in the fan reach of 18.4 m, was to be concentrated at the dam sites, dissipating half of the reach energy across 20:1 sloping tailraces of large (20 - 50 cm) fieldstone (Figure 4A).

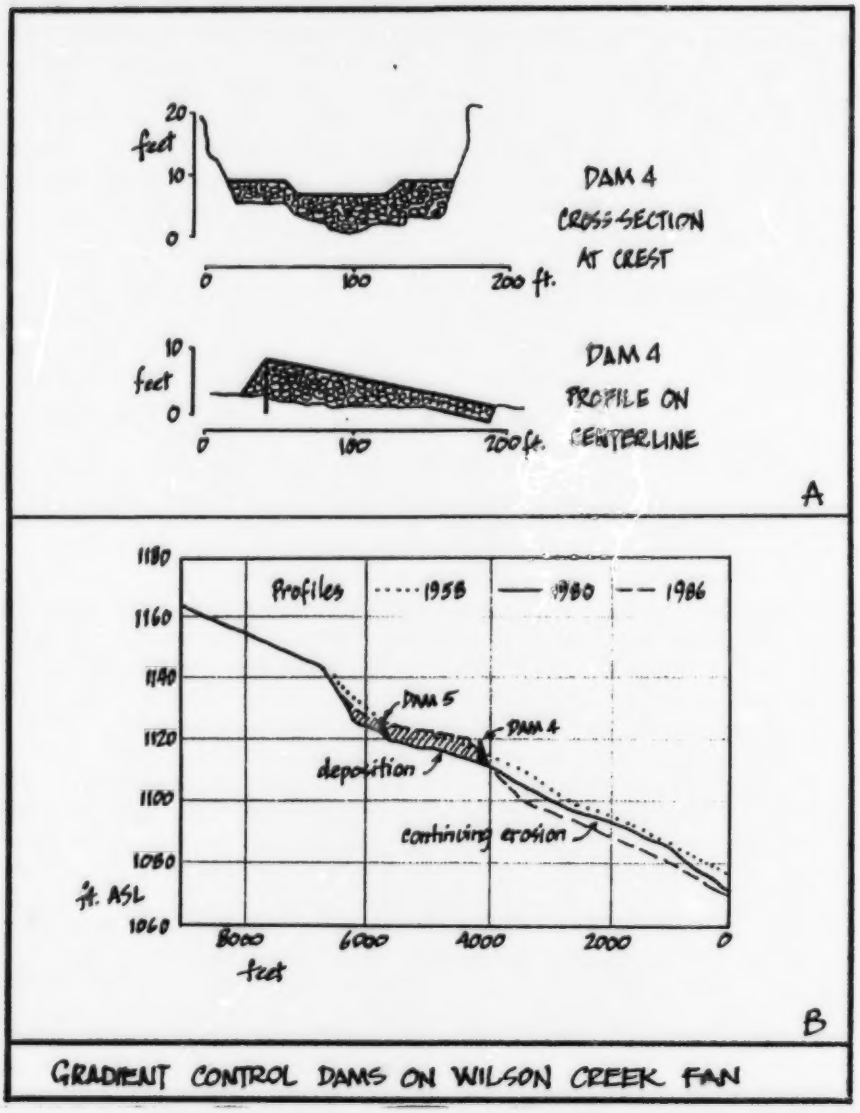

Figure 4: The Wilson Creek experimental gradient control dams are constructed of cobbles and boulders that have been cleared from the adjacent agricultural fields. In the two reaches above the dams, the gradient of the stream has been reduced from .008 to .004, stopping further erosion of the alluvial fan deposits.

The upper two dams, numbered 4 and 5, were constructed in 1980 (Figure 3). In the reaches above the dams, all erosion of the channel bottom and sides ceased, and by 1986, deposition of new sediments from the escarpment in the reaches upstream of the dams had re-established the natural fan gradient of 0.4 percent (Figure 4B). As the first three dams were not constructed, erosion of the channel bottom and sides continued below dam 4 at the same rate as the whole fan reach had been eroding prior to 1980 (Bowering 1987). In the 1980 - 86 period, the eroded

materials from the un-adjusted reach were removed three times from the low gradient Wilson drain a few km further downstream.

Similar reaches of headcutting and degradation in alluvial fans occur along the foot of the escarpment, particulary below the steep Riding Mountain segment. Surveys to identify the erosion sites and establish their pre-channelized natural gradients and geometry are currently being conducted to develop a general programme for fan re-stabilization wo ks (Chapman 1987b).

2) Fieldstone Riffles To Re-create Natural Pool And Riffle Hydraulic Habitats For Spawning And Egg Incubation On The Mink River

The tightly meandering lower Mink River (Figures 1 and 5) was straightened and uniformly graded in 1950 to increase the flood capacity of the main channel. A typical channelized reach through section 26, township 28, range 19w is shown in Figure 6 in 1949 before construction and in 1984 after several re-constructions. The channel length between the boundaries of section 26 was reduced from 2133 m to 1734 m by straightening. The net change in channel gradient after 24 years was from 0.19 percent to 0.22 percent. Two designs for the channelized cross-section were constructed as shown in Figure 7 at a typical cross-section in the south-west quarter of section 26. In the initial design, the natural channel was reduced in width and deepened with 2:1 side slopes and a 30 foot base (1951, Figure 7). In the next thirty years, increasing flood flows from the cleared and expanded lower Mink River basin degraded the channel profile, causing the banks to steepen and slump (1982, Figure 7). In 1984, the channel was re-constructed with 4:1 side slopes and a 6m base (1984, Figure 7). During this period, the bankfull flow velocity and discharge capacity was increased from 1.0 to 2.1 m per sec and 17 to 76 cubic m per sec respectively, based on Manning's equation and roughness coefficients for natural streams and excavated channels (Chow 1959). The tractive force acting upon the channel bed materials

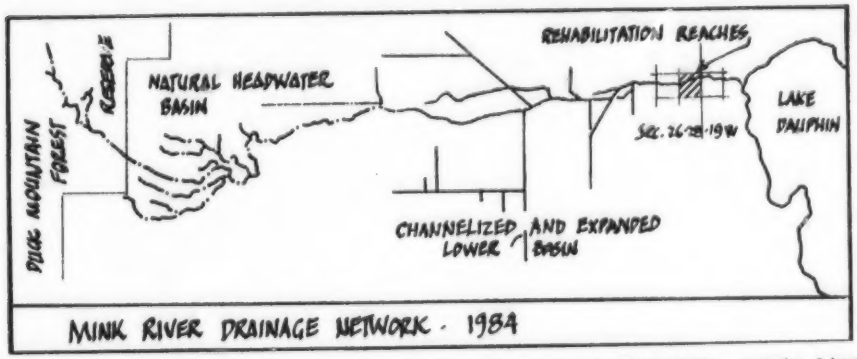

Figure 5: The Mink River drainage basin. The natural headwater basin lies in the Duck Mountain segment of the Manitoba escarpment. Fieldstone riffles have been constructed at three experimental rehabilitation sites near Lake Dauphin in the channelized lower reaches of the river.

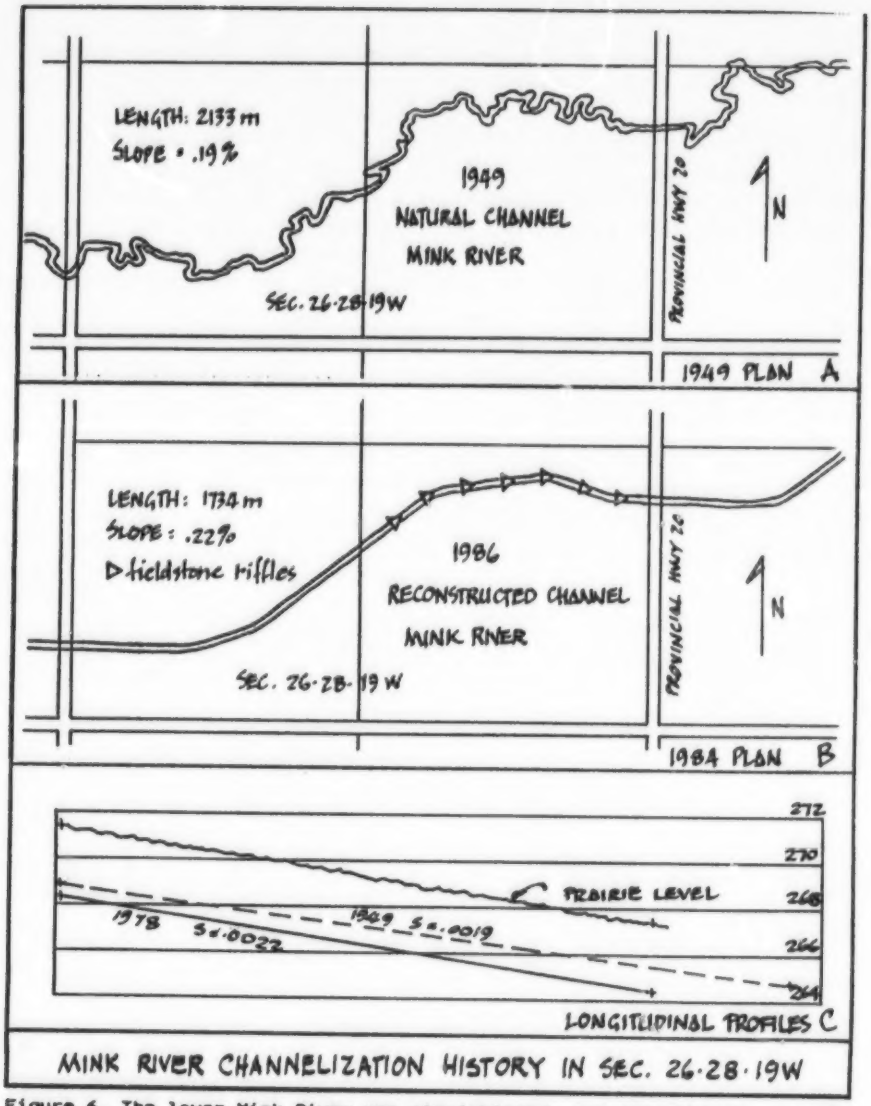

Figure 6. The lower Mink River was straightened and channelized in 1951, increasing the channel gradient and removing the pool and riffle configuration of the natural stream bed. Experimental fieldstone riffles were constructed in the channel in 1986 to decrease channel erosion and to restore part of the natural habitat for fish spawning and egg incubation.

at the bankfull stage increased from 2.1 to 3.4 kg per square m, which continues to degrade the channel bottom by removing the finer fraction of the glacial till bed materials.

In 1985 and 1986, three channelized reaches were selected for rehabilitation in sections 25, 26, and 27, township 28, range 19w (Figure 5). A representative reach is shown in Figures 6 to 10). Riffles were constructed in each reach at intervals of approximately 100 m using cobbles and boulders hauled from local stonepiles that had been collected in the surrounding fields.

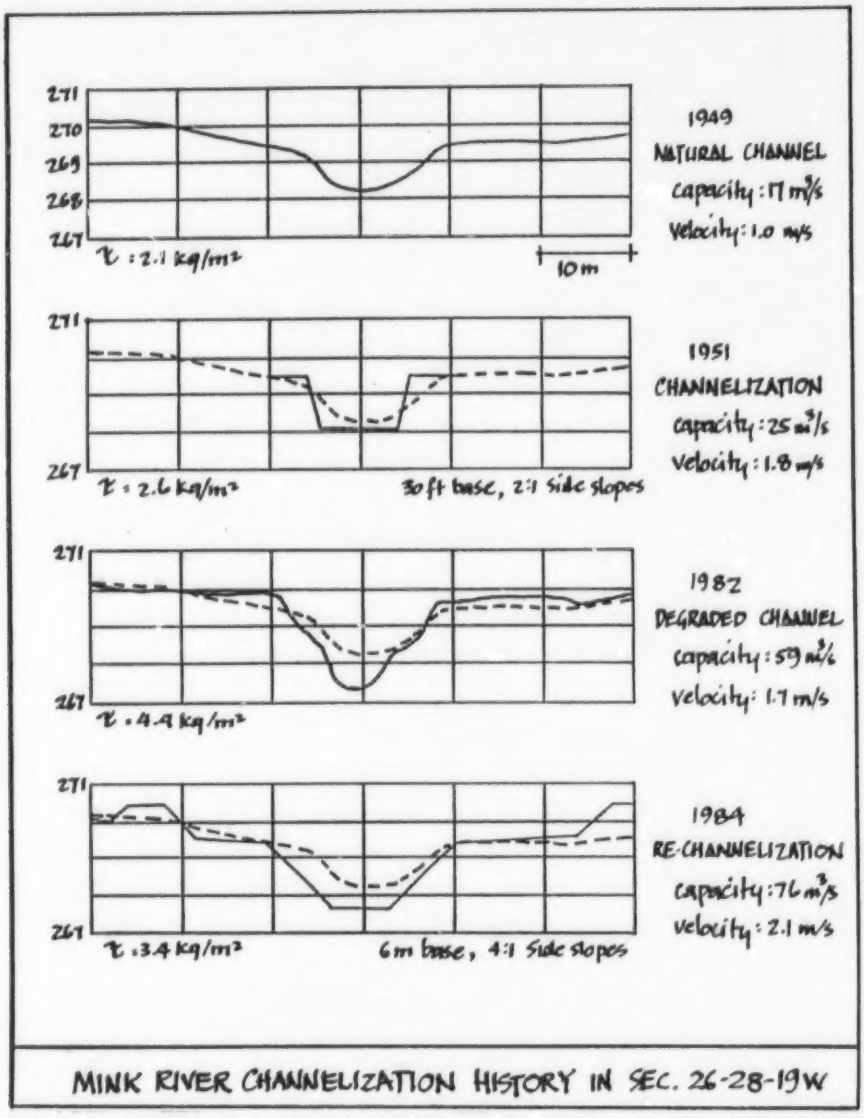

Figure 7: Changes in a typical channel cross-section in the rehabilitated reach in section 26 - 28 - 19w show the evolution of the channel from a wide and shallow natural section to a steeper and narrower channelized form, followed by 21 years of erosion and bank slumping until a wider cross-section was established. The 1984 reconstructed channel is similar to the original natural section but at a lower elevation.

The crest elevations of the riffles follow the gradient of the re-constructed channel but each riffle is of sufficient height to create a pool that extends half-way up the downstream face of the next riffle upstream. This created a pool and riffle spacing that was approximately 6 times the bankfull width of the pre-development channel which is similar to the spacing observed in many natural streams (Leopold, Wolman and Miller 1964). The rehabilitated pool and riffle reach in section 26 is shown in Figure 6b in plan, Figure 8b in profile and Figure 9 in a photograph taken at a discharge of 2.1 cubic m/sec.

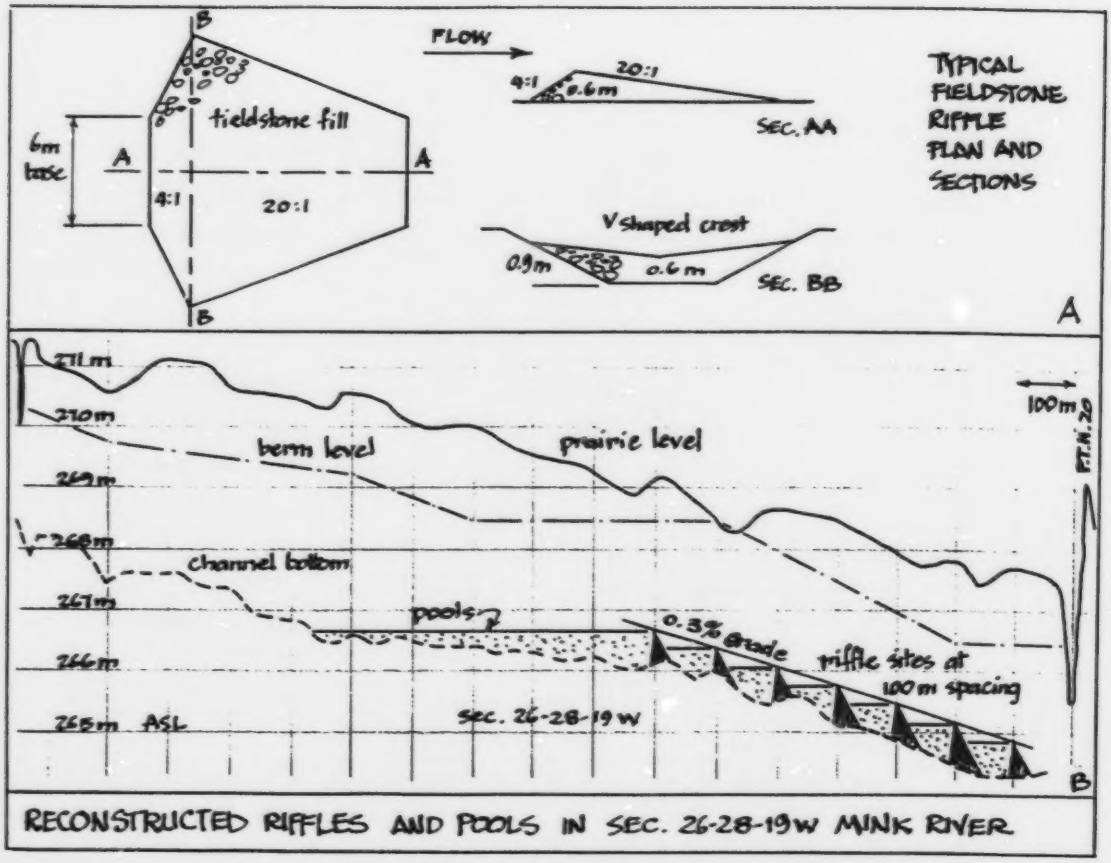

Figure 8: Experimental fieldstone riffles were constructed in the steeper part of the Mink River channel in section 26 - 28 - 19W in 1986. The riffles were spaced at 100 m intervals to create pools and riffles similar to those of the pre-channelized natural streambed. The energy loss on the fieldstone at each riffle site reduced the stream gradient in the upstream pool, stabilizing the channel at bankfull flood flows.

The downstream face of the riffles was built to a shallow 20:1 slope as this gradient was observed not to obstruct the upstream passage of spawning walleye (Stizostedion vitreum) in the natural rapids of the nearby Valley River.

In 1986, the peak flow from spring snowmelt runoff of 13 cubic m/sec was followed four weeks later by a rainstorm runoff peak of 41 cubic m/sec which filled the channel to the bankfull stage in the pool and riffle reaches. None of the riffles were displaced by the flood flows, although one required some additional fill when settlement occurred on one bank. No bank erosion occurred in the rehabilitated reaches but below each riffle, a scour hole approximately 1 m deep and 12 m long was formed in the downstream pool. In the reaches of the channel above and below the rehabilitated riffle sections, bank erosion and slumping were severe during the peak flow period, requiring further re-construction of the 4:1 side slopes. There was no further erosion of the riffles or downstream scour holes by the 1987 bankfull spring runoff peak.

Figure 9: The experimental pool and riffle reach in the channelized portion of the Mink River in section 26 - 28 - 19w. Five fieldstone riffles 0.6 m in height, spaced at 100 m intervals are visible along the channel. The vertical drop between riffles is 0.3 m, creating an upstream pool that extends onto the lower face of the next riffle upstream.

DISCUSSION

Benefit / Cost Analysis

The direct benefits of the two gradient control dams on the Wilson Ceek fan in terms of reducing re-excavation costs in the drainage system below were evaluated by Bowering (1987) following an infrequent peak runoff event in 1986. Based on a capital cost of $23,500 and an average annual maintenance cost of $1,000 for each dam, the benefit/cost ratio was estimated to be 1.3 for a discount rate of 5 percent. Indirect benefits more difficult to assess include the prevention of further farmland erosion adjacent to the degrading channel and the reduction of sedimentation in downstream channels and lakes with sport and commercial fisheries.

The benefit/cost ratio of the Mink River rehabilitation works in terms of the direct benefits of channel stabilization can only be determined by further surveys and monitoring of the rehabilitated and non-rehabilitated reaches over a series of peak runoff events. During the one peak flow event that occurred in 1986, there was no significant erosion in the reconstructed pool and riffle reaches. However, in the reaches immediately above and below the rehabilitation site, erosion of the channel bottom caused slumping to occur along approximately 30 percent of the banks. Reconstruction of the banks in the adjacent reaches,

using Wilson Creek excavation costs of 1 dollar per cubic yard, would cost approximately $150 per 100 m of reach. The average cost of a riffle, creating a 100 m pool with stable banks, was $800, suggesting that over a 6 year period of spring runoff and other peak events, the cost of the riffles would be recovered. This does not include the primary benefits to fisheries rehabilitation.

Biological Response

Increased sedimentation rates decrease fish egg survival (Gaboury 1985) and degrade the species complex of lake fish communities (Trautman 1957). Gradient control dams in the alluvial fan reaches below the Manitoba escarpment similar to those constructed on Wilson Creek will reduce sediment inputs to larger downstream channels and lakes used for fish spawning and rearing. Locally, the dams create small temporary impoundments that may be stocked for local recreational fishing until the reservoirs are filled with shale sediments from the escarpment. For the downstream dams, this may not occur for several decades. Infilling of the reservoirs, as at dam 5 on Wilson Creek, does not reduce their effectiveness in adjusting the channel gradient. On Wilson Creek, other non-aquatic habitats are evolving on the upper reservoir surface as the canyon sides stabilize and re-vegetation occurs. When the remaining control dams have been built, there will be significant changes to the more stable upper drainage canal as well, as frequent re-excavation will not be required.

The straightening of meandering channels and uniform grading of pool and riffle reaches by channelization eliminates a variety of channel bed forms and flow configurations that occur in natural stream channels (Nowell and Jumars 1984). The subsequent loss of biologically significant habitats, or reduction in habitat diversity, has been shown to reduce the number of fish species present in the stream (Karr and Schlosser 1978, Swales 1980) and to alter the zonation and productivity of benthic invertebrate communities (Statzner and Higler 1986). Portt et al. (1986) and Congdon (1971) found that fish biomass in channelized stream reaches was reduced by up to 80 per-cent as compared to non-channelized reaches. The suggested factors that were responsible for the reductions were; loss of channel area, removal of riffles, decreased habitat diversity, and instability of substrate, water temperatures, and water levels. Other studies have shown that the creation of riffles and pools in channelized streams have accelerated the recovery of benthic macroinvertebrates and fish populations by restoring the substrate composition and stability and creating cover and diverse habitats in previously uniform channels (Barton and Winger 1973, Griswold et al. 1978).

The scale of the hydraulic conditions created by the rehabilitation works is an important factor in their design. The rehabiliation of benthic habitats, for example, requires that individual cobbles and boulders be arranged on the stream bed to create specific local flow variations that are preferred by selected organisms (Nowell and Jumars 1984). The creation of spawning riffles requires larger scale manipulation of the flow pattern, in the horizontal plane as well as the vertical plane. Studies of spawning behaviour in streams have determined that walleye spawn on the edges of horizontal eddies (Gibson and Hughes 1977, Stepaniuk in press). On the re-constructed riffles on the Mink River, walleye were observed to use three eddy locations; on both sides of the pool immediately upstream of the riffle crest, behind large cobbles and boulders on the riffle surface, and in the large back eddies formed on the downstream face of the riffles at the upper end of the downstream pool. As shown in the photograph in Figure 10, the large eddies are formed because the v-shaped crest of the riffle (Figure 8A) concentrates the flow in the center of the channel as it accelerates towards the crest and decelerates into the pool below.

Figure 10: The v-shaped crest of the experimental riffles concentrates the flow in the center of the channel, causing large horizontal back eddies to form on the downstream face of the riffle and in the upper end of the pool below. Fish spawning activity was observed along the edge of the eddies.

In 1986, in a reach located further upstream in section 27-28-19w, additional riffles were built in pairs, 20 and 50 m apart, to create a short central pool with enlarged eddies on each bank that extended from the upper riffle to the face of the downstream riffle. Based on egg density measurements, more

walleye spawned on the paired riffles (3.6 eggs/square m) than on the single riffles (1.1 eggs/square m). Also, the number of newly hatched walleye larvae caught below the paired riffles was significantly greater than the number caught below any of the single riffles.

In channelized streams, bed instability, bank erosion, and sedimentation below headcutting reaches are often severe when the natural channel gradients are steepened and the flow resistance decreased (Chapman 1987a). Following channelization, the flow velocity at the bankfull stage in the Mink River has doubled (Figure 7), causing large numbers of deposited eggs to be swept downstream from the uniformly constructed reaches during the annual spring peak flow period (Table 1). In contrast, egg drift through the rehabilitated pool and riffle reaches was considerably lower because of the increased opportunities for eggs to settle behind and adjacent to the larger boulders on the riffle surface and in the low velocity zones created in the horizontal eddies above and below the riffle crests. Egg survival and larvae production in the riffle zones is also enhanced by the aeration of water as it flows across the riffle surface and by higher local velocities that prevent sedimentation and consequent egg suffocation.

TABLE 1

Drift trap catches of walleye eggs per 24 hours in sections 25, 26, and 27 - 28 - 19w, Mink River 1986.

Date	Unimproved Channel		Rehabilitated Channel	
	sec 27	sec 26	sec26	sec25
April 30	1020	1236	36	0
May 1	255	60	0	0
2	168	558	0	0
3	222	252	92	0
5	124	0	40	0
6	60	63	0	0
8	117	305	50	0
9	-	37	18	6
10	55	125	65	0

The re-creation of a natural stream in straightened and channelized reaches can be only partially achieved without using adjacent farmlands to re-form meander loops or without reducing flood capacities by re-vegetating the channel sides. In some cases, these measures may be justified by the value of the biological resources (Glitz 1983). The pool and riffle sequences created on the Mink River selected only one characteristic of the pre-development channel to re-create spawning and egg incubation habitats that would also stabilize the channel and not require additional land or channel re-construction.

Natural Stream Characteristics

The use of natural stream characteristics and behaviour in designing rehabilitation works often relies upon having records of the pre-development conditions in the channelized stream. When surveys of the natural stream are not possible, reference must be made to the general behaviour and characteristics of streams in similar regional climatic and geologic settings. In the case of Wilson Creek, the natural stream system has not been altered in the headwater reaches within Riding Mountain National Park, providing an opportunity to survey the tributary branches of the creek and determine relationships between bankfull width, depth, velocity, and discharge and the tributary drainage area for escarpment streams. These relationships, referred to as the hydraulic geometry of the stream, are similar to general relationships developed elsewhere as shown in Figure 11 (Dunne and Leopold 1978). The width and depth of the typical pre-channelized Mink River cross-section shown in Figure 7 also agrees with the generalized relationships.

Once the hydraulic geometry relationships are established, the basin area and stream profile taken from topographic maps or surveys, can be used to discover if local reaches of anomolously high erosive power exist under bankfull flow conditions as in the case of the channel through the Wilson Creek alluvial fan. On the Mink River, the bankfull width was used to determine the pool and riffle spacing, which appears to have been stabilized and reinforced by peak flows. The continued widening of the adjacent unaltered reaches of the river suggests that although narrow, deep channels provide the best hydraulic radius for conducting flood flows, natural channel cross-sections are wider and shallower with general width to depth ratios of approximately 15:1 for streams with drainage areas of less than 100 square miles in this region.

Field surveys of stream channels may be used also to determine biological habitat characteristics, used for example in setting instream flow requirements (Bovee and Cochnauer 1977) or in preparing regional stream habitat inventories (Pfankuch 1978). The hydraulic geometry of Wilson Creek and other escarpment streams, used in designing the rehabilitation works, was

determined by conducting simplified reach surveys (Newbury 1984, 1985) in streams with drainage basin areas that ranged from 3 to 230 square km. The survey procedures and data sheets are summarized in Figure 12 for stream enthusiasts.

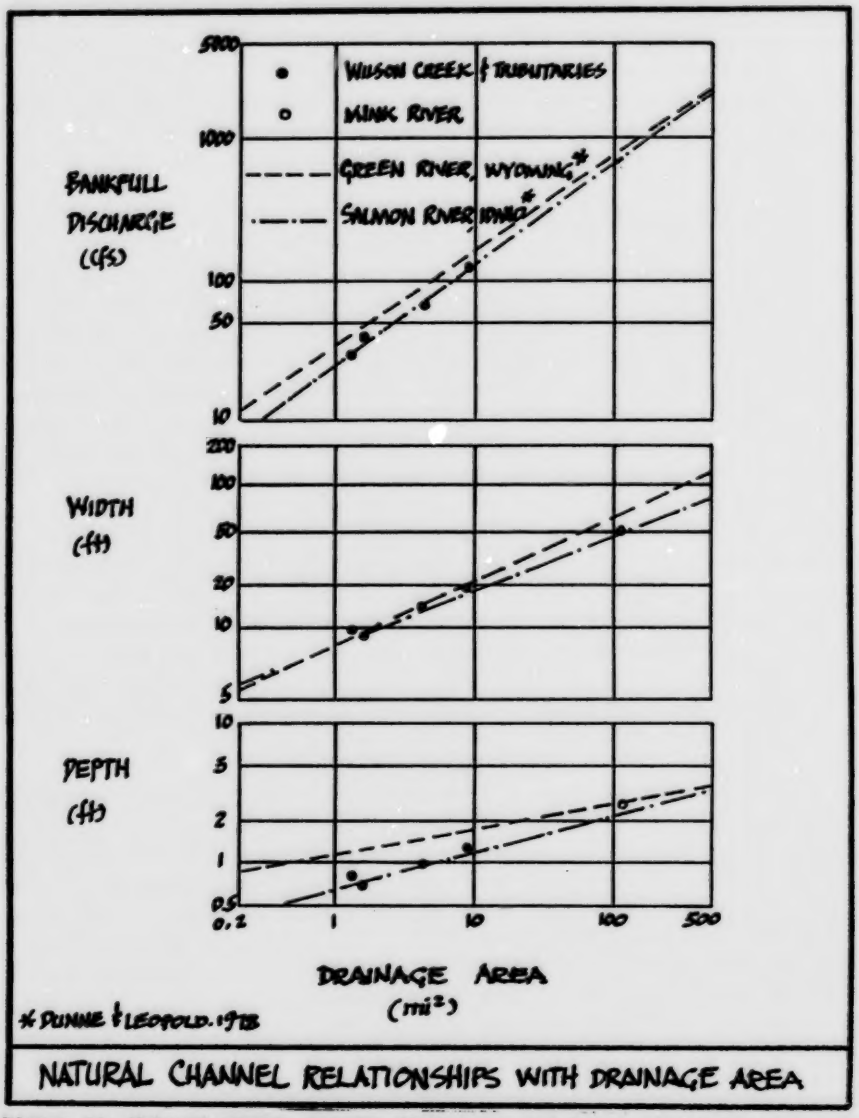

Figure 11: Natural stream channel dimensions and flood capacities increase with increasing drainage basin size. The relationship between the drainage area and the natural bankfull channel characteristics may be derived from field surveys over a range of channel sizes as shown for the Wilson Creek tributaries and other similar stream networks. The natural characteristics can provide useful guidelines for the design and location of stream rehabilitation works.

HYDROLOGY A Date

Stream Name

Location

A. Present Discharge

Cross Section of metered flow

Average Velocity, $\bar{V}$ = m/sec

Area, A = m^2

Q_{pres} = m^3/sec

n_{pres} =

B. Present Flow

x-sec 1

x-sec 2

x-sec 3

x-sec 4

x-sec 5

Present Average Depth, $\bar{d}$ = m

Present Average Width, $\bar{w}$ = m

	Riffles Length	Riffles Slope	Pools Length	Pools Slope
1.				
2.				
3.				
4				

Total Length = Average Slope =

C. Stream Bed

X_{cm}	Y	Z	$\bar{\emptyset}$	Rank

HYDROLOGY B	Stream Name	Location	Date

Skeich 1cm ≈ 10m

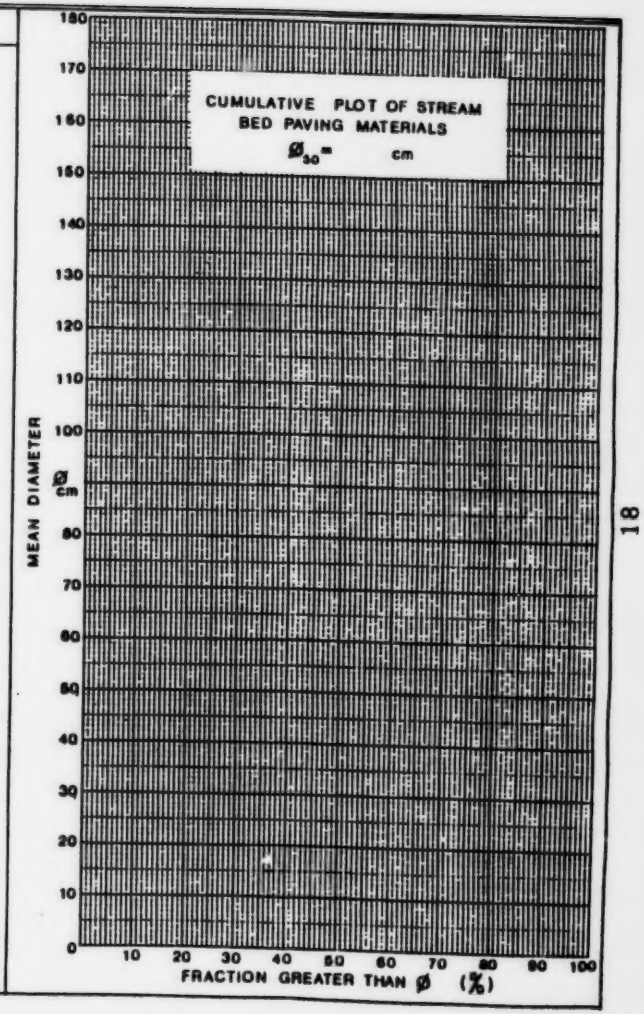

Figure 12B: (see caption Figure 12A)

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